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NEUTRONIC CALCULATIONS OF FUEL AND POISON DRUM CONTROL OF REFRACTORY-METAL, FAST-SPECTRUM, SPACE POWER REACTORS

by Robert M. Westfall and Wendell Mayo

Lewis Research Center
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ABSTRACT

An analytical procedure was developed to evaluate drum control worths with one-dimensional, radial, discrete ordinate (S_n) transport calculations. Two types of drum control were evaluated, one with fuel drums containing a heavy-metal reflector material, the other with poison drums containing beryllium oxide and boron carbide. The one-dimensional procedure gave small-core drum control worths which agree with two-dimensional calculations to within 7 percent. The control response curves from two-dimensional calculations agree with $\sin^2(\theta/2)$ curve to within 15 percent. Poison control drum worths are sufficient for 40-centimeter-diameter cores. Fuel control drums are applicable to cores as large as 80 centimeters in diameter.

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SUMMARY

An analytical procedure was developed to allow the use of one-dimensional, radial calculations to determine the reactivity control that is obtainable by rotating reflector drums. Two types of drums were evaluated. One type contains a heavy-metal reflector material with fuel elements; the other contains beryllium oxide with boron carbide as a neutron absorber.

The large number of mesh points required to describe control drum geometries precludes two-dimensional, discrete ordinate (S_n) transport programs for preliminary design calculations, especially for the larger cores. Therefore, criteria were established for setting up one-dimensional geometries which give adequate results. A check was made on the one-dimensional model by comparing the calculated control change for a 16.5-centimeter-equivalent-diameter core with values obtained from two-dimensional calculations. The fuel and poison drum control worths of 7.5 and 11.4 percent $\Delta k/k$ agree to within 7 percent with two-dimensional calculations of 7.3 and 12.3 percent $\Delta k/k$. The control worths are expressed as the percentage variation of the calculated multiplication factor k that results from drum rotation away from the minimum value.

The one-dimensional model was then used to analyze both types of drum control on 40- and 80-centimeter-diameter cores. All configurations analyzed were capable of providing in excess of 7 percent $\Delta k/k$ control with two exceptions. The first exception is a small-core poison drum configuration in which the drum diameter is reduced to the fuel drum diameter used on the same core. The poison drum control swing of 4.6 percent $\Delta k/k$ shows that poison drums are less effective than equal-size fuel drums (7.5 percent $\Delta k/k$). The other exception is the 3.8 percent $\Delta k/k$ control swing of the poison drums on the 80-centimeter-diameter core. This value is decreased from 8.45 percent $\Delta k/k$ by a 2-centimeter-thick refractory-metal pressure vessel.

Additional information presented includes the shapes of the control response curves, maximum local power densities, the effects of peripheral radial shielding material on the control, and the effects of the energy group distribution and the P_l, S_n approximations on the calculated multiplication factors.

INTRODUCTION

Control of small fast-spectrum reactors with reflector control drums containing a neutron absorber, such as boron-10 carbide ($^{10}B_4C$), and a neutron moderator, such as beryllium (Be) have been frequently considered. In most of these considerations the neutronic calculations have been made by assuming annuli of moderator and absorber so that a one-dimensional, radial model could be used. With the optional one- or two-dimensional geometry in the discrete ordinate transport theory (TDSN) program (ref. 1), it is possible to check this annular model assumption for small cores. Once this is done, it should be possible to develop a recipe for annularizing that might be reasonably accurate for calculating various aspects of larger control drum cores. This possibility was investigated in this report.

At the present time there are no fast reactors with highly moderating neutron reflectors which have ever been operated at power. There is, however, considerable operating experience with moving fuel as the reactivity control mechanism. The EBR-II and Dounreay reactors (ref. 2) are examples of fast reactors that are controlled with the movement of fuel. In order to relate to this operating experience, a second drum control method for compact cores was investigated. This method consists of trying to isolate fuel from the core by moving it radially outward in a control drum that also contains a heavy-metal reflector material.

A configuration representing each type of drum control was analyzed for core diameters of approximately 17, 40, and 80 centimeters. Two-dimensional calculations were made only on the 17-centimeter core to check the annularizing criteria. The reactors are of a type that is being considered for high-temperature, space power generation (refs. 3 and 4). The refractory-metal structural materials contain either uranium-233 oxide or nitride fuel ($^{233}UO_2$ or ^{233}UN) and a lithium-7 (^{7}Li) coolant. The particular sizes and compositions of the several configurations reflect differing power and lifetime capabilities.

The effects of energy group distribution and the degree of the P_l and S_n approximations were also investigated. Supplementary information including control response curves, power ratios, and the effects of radial shielding materials on the control swing worths is reported. The scope of this report, however, does not include the determination and optimization of a complete reactor control system.

DRUM DESIGN CONSIDERATIONS

Fuel Drum Configuration

The fuel drum concept, for example figure 1, includes a refractory-metal reflector,

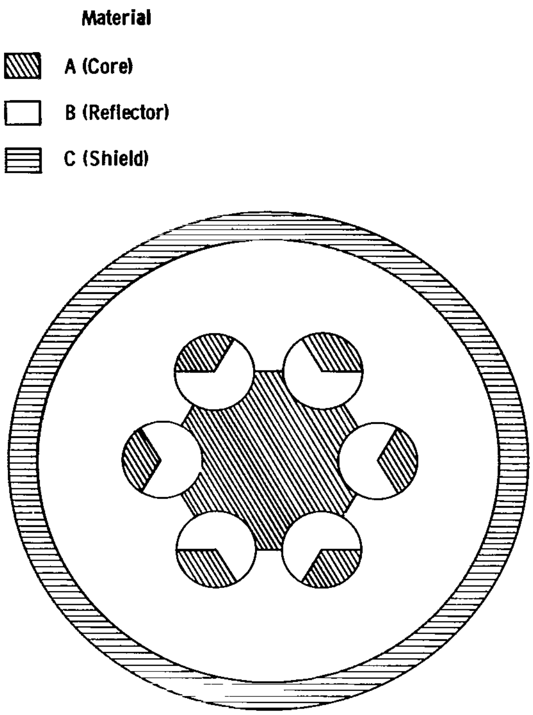

Figure 1. - Radial cross-section view of small core with fuel drums.

portions of which are in the drums. Negative reactivity is inserted by rotating the fuel segment out of the core and replacing it with the reflector. The fuel is moved to a less important position, and it is partially masked from the core by the reflector portion of the drum. Since the peripheral fuel decreases in importance as the core diameter is increased, the control drums must contain a larger percentage of the core volume to maintain the same control swing. The fuel portions of the control drums for the 17-, 40-, and 80-centimeter-diameter cores represent 29, 38, and 47 percent of the respective core volumes.

Poison Drum Configuration

The poison drum concept, for example figure 2, includes a neutron-moderating beryllium oxide (BeO) reflector and a refractory-metal pressure vessel which provides a heat barrier between the core and the reflector. Neutron moderation by the BeO enhances the control worth of the $^{10}B_4C$ poison. The control drums contain segments of the poison and the reflector; upon rotation the reflector masks the $^{10}B_4C$ portion of the drums for positive reactivity insertion. Under exposure to irradiation, the BeO tends to

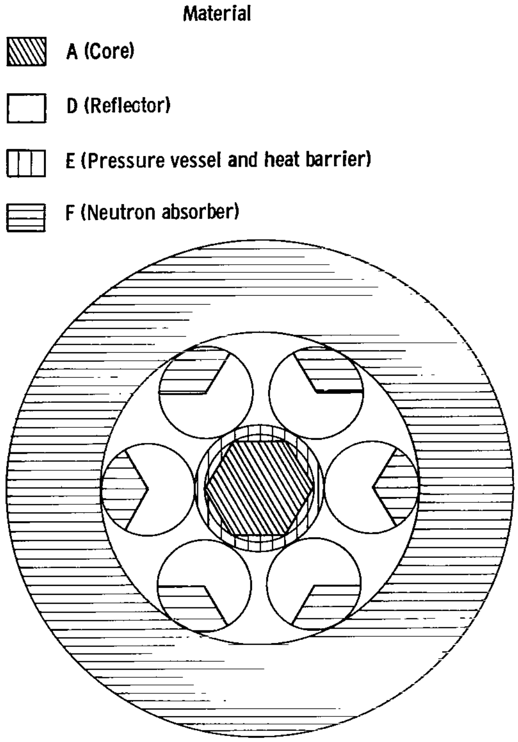

Figure 2. - Radial cross-section view of small core with poison drums.

break into a powder after a dosage of about 10^{21} fast neutrons per square centimeter (ref. 5). Also a large quantity of helium gas will be generated through neutron absorption over long operating times. Therefore, the reflector design for the larger, longer-lifetime cores includes a molybdenum (Mo) canning material and a large void fraction to contain the BeO and the generated gas.

The control worth of this type of drum system is directly dependent upon the overall worth of the radial reflector and how effectively the reflector worth can be changed by rotation of the drums. The radial reflector worth decreases as the core diameter increases. Therefore, the effectiveness of the poison drum systems must be greater for the larger reactors. One way to increase the drum effectiveness is to mask the outer surface of the core more completely with smaller, more closely spaced drums. Therefore, the poison drum configurations for the 17-, 40-, and 80-centimeter-diameter cores have 6, 8, and 12 drums, respectively.

A problem associated with the use of a BeO reflector with a fast-reactor core is the presence of a thermal-neutron power spike at the edge of the core. Since the configurations studied herein include refractory-metal pressure vessels between the core and the BeO reflectors, the power spike does not occur. However, the pressure vessels reduce the reflector worths and, subsequently, the control swings. An optimized poison drum control system of the type presented herein would include a minimum-thickness pressure vessel to provide adequate strength, a sufficient thermal barrier between the high-temperature core and the BeO reflector, and a sufficient thermal-neutron capture area to reduce the power spike to acceptable levels. Such an optimization procedure is beyond the scope of this work.

ANALYTICAL PROCEDURE

Model Development

The maximum number of mesh cells available for running a two-dimensional, S_2, P_o, 4-energy-group calculation with the TDSN program (ref. 1) on a 32 000-word memory class computer is about 1400 (38 by 38 grid). This limitation precludes the calculation of large complicated geometries in two dimensions.

The development of the one-dimensional model for these geometries primarily involved the establishment of a procedure for accounting for the regions of azimuthal asymmetry in the radial plane. An integral quantity such as the neutron multiplication factor k_{eff} can be calculated by annularizing the region boundaries and homogenizing the constituent materials. Three criteria were selected to carry out these procedures:

(1) In configurations with a core geometry which differs from a right circular cylinder, a circular cylinder of the same height and equal volume is assumed. Then the following criteria are applied.

(2) The total number of atoms of each material in the entire configuration is conserved.

(3) The boundaries of each annular region are located at the actual radial extremities of the core and control drum regions. The homogenization procedure is then applied to the materials lying within the annular regions.

The evaluation of the one-dimensional model was made by comparison of one- and two-dimensional calculations of the drum control worths on the small core. One-dimensional studies were made of the effects of varying the number of energy groups and the order of the S_n and P_l approximations used in the discrete ordinate transport solutions. These results were then used in the two-dimensional calculations. Presentation of these effects, as well as descriptions of the one- and two-dimensional geometries and the results of the evaluation, are included in subsequent subsections on the analytical procedure.

Drum Configurations With 16.5-Centimeter-Equivalent-Diameter Core

The small-core geometries with the fuel and poison drums are shown in figures 1 and 2. The material descriptions and compositions are given in table I. The reactor

TABLE I. - SMALL-CORE MATERIAL DESCRIPTIONS

Material designations and constituents	Nuclide	Atom density, atoms/(b-cm)
Material A (core), vol. %:	^{233}U	0.014514
51 ^{233}UN - 49W, 86.5	N	.014514
W cladding, 3.25	W	.02884
^{7}Li coolant, 10.25	Li	.004746
Material B (W reflector), vol. %:		
W, 95	W	0.06004
^{7}Li, 5	^{7}Li	.0023
Material C (^{6}LiH poison region;	^{6}Li	0.0606
fully enriched in ^{6}Li)	H	.0606
Material D (BeO reflector), vol. %:	Be	0.06916
BeO, 95	O	.06916
^{7}Li, 5	^{7}Li	.0023
Material E (T-222 pressure vessel), wt. %:		
Ta, 87.5	Ta	0.029576
W, 10.0	W	.003326
Hf, 2.5	Hf	.000856
Material F ($^{10}B_4C$ poison region, fully	^{10}B	0.10526
enriched in ^{10}B), vol. %:	C	.026315
$^{10}B_4C$, 95	^{7}Li	.0023
^{7}Li, 5		

core is the same for both configurations. A hexagonal-core cross section was chosen for ease of representation in the two-dimensional rectangular geometry. The major diameter of the hexagon is 18.16 centimeters which corresponds to an equivalent circular diameter of 16.51 centimeters on an area conservation basis. The height of the core is 44.06 centimeters.

The fuel drum configuration includes a 10.16-centimeter-thick tungsten (W) radial reflector. Located at the corners of the hexagonal core are six, 6.35-centimeter-diameter control drums, each containing a 120° sector of the core material. Exterior to the reflector is a 2.5-centimeter-thick region of lithium-6 hydride (^{6}LiH) shielding material.

The poison drum configuration has a pressure vessel extending from the core surface to an outer diameter of 20.68 centimeters. The $^{10}B_4C$ drums are located in a 15.24-centimeter-thick BeO reflector. The $^{10}B_4C$ is contained in 120^o sectors of the drums. The reflector is surrounded by 15.24 centimeters of $^{10}B_4C$ representing radial shielding material.

One-Dimensional Geometries

The small-core, drums-out geometries are shown in figures 3 and 4. Table II contains the material volume fractions of the fuel-reflector and poison-reflector regions. The core region was maintained at full material density with the equivalent-area circle representing its outer boundary. The criteria listed in the subsection on model development were followed in setting up the one-dimensional annular regions containing the control drums.

In each control drum representation, successive annular regions represent the drums-in and drums-out geometries. The fuel drum annuli are divided at the equivalent radius of the core, while the poison drum annuli are divided at the actual drum centers.

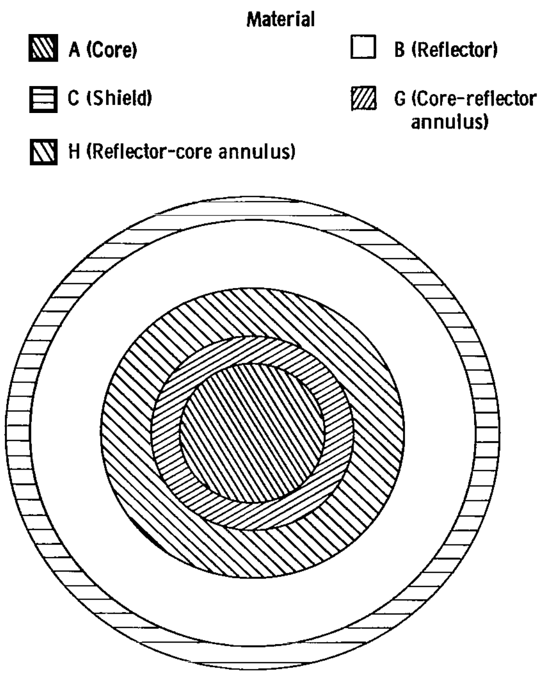

Figure 3. - One-dimensional representation of fuel-drums-out configuration of small core.

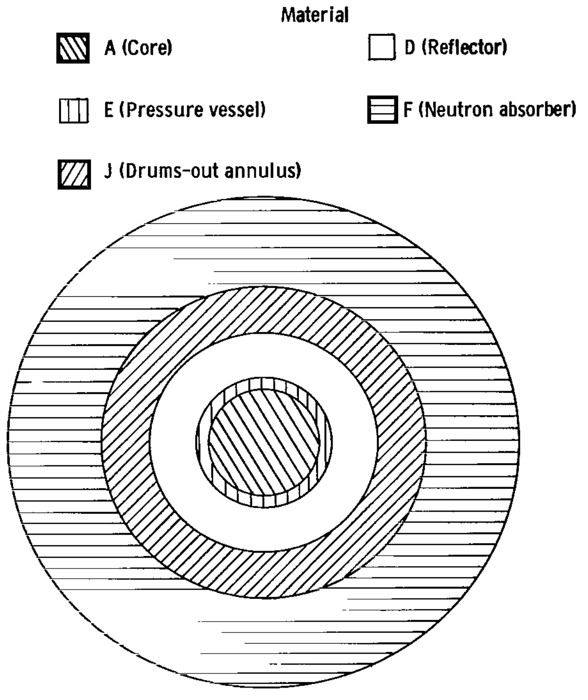

Figure 4. - One-dimensional representation of poison-drums-out configuration of small core.

TABLE II. - SUPPLEMENTARY MATERIALS FOR

ONE-DIMENSIONAL, SMALL-CORE

CALCULATIONS

Material G (inner core-reflector annulus), vol. %:
Material A, 39.47
Material B, 60.53
Material H (outer reflector-core annulus), vol. %:
Material A, 24.59
Material B, 75.41
Material I (drums-in, $^{10}B_4C$ - BeO region), vol. %:
Material D, 46.18
Material F, 53.82
Material J (drums-out, $^{10}B_4C$ - BeO region), vol. %:
Material D, 65.01
Material F, 34.99

Effect of Energy Group Distribution and P_l, S_n Approximations on Calculated Multiplication Factors

The large number of mesh intervals required in two-dimensional calculations restricts the number of energy groups that may be used, as well as the degree of sophistication of the S_n and P_l approximations used in the solution of the Boltzmann transport equation. A series of one-dimensional calculations was carried out to establish the adequate calculation level for each type of drum control.

The fast and epithermal cross sections used in these calculations were calculated with the GAM-II program (ref. 6). The thermal cross sections used to analyze the BeO reflected configuration were calculated with the GATHER-II program (ref. 7). The energy group boundaries for the cross sections are given in table III. The scattering cross sections were represented by the Legendre polynomial expansion through P_1. The calculations were done with the S_2 and S_4 moment modified quadratures in the discrete ordinate transport theory program (TDSN, ref. 1).

Table IV gives four multiplication factors for the fuel-drums-in configuration which represent levels of calculation that vary from S_4P_1-13 energy groups to S_2P_0-4 energy groups. The least sophisticated calculation gives a multiplication factor which is 0.47 percent $\Delta k/k$ (see definition in table IV) greater than the value given by the most sophisticated calculation. Multiplication factors for the intermediate levels of calculation indicate the portions of the total effect resulting from the various approximations. Reducing

TABLE III. - ENERGY GROUP BOUNDARIES[a]

FOR 14-, 13-, 8-, AND 4-GROUP SETS

Group	Upper energy boundary, eV	Group	Upper energy boundary, eV
1	14 918 250	8	183 156.4
2	3 678 795	9	111 090.0
3	2 231 302	10	40 867.73
4	1 353 353	11	15 034.40
5	820 850.1	12	5 530.846
6	497 870.8	13	748.5186
7	301 973.9	14	.414
			0

[a]The 13- group set does not include group 14; the 8-group sets has upper energy boundaries at groups 1, 5, 8, 10, 11, 12, 13, and 14; the 4-group set has upper energy boundaries at 1, 5, 8, and 10.

TABLE IV. - MULTIPLICATION FACTOR FOR SMALL CORE

WITH FUEL DRUMS IN AT VARIOUS LEVELS

OF ONE-DIMENSIONAL CALCULATION

Index, i	Level of calculation	Neutron multiplication factor, k_{eff}	Control swing,[a] percent $\Delta k/k$
1	S_4, P_1, 13 groups	1.11104	----
2	S_4, P_0, 13 groups	1.11959	0.77
3	S_4, P_0, 4 groups	1.11881	-.07
4	S_2, P_0, 4 groups	1.11631	-.23
		Total effect	0.47

[a]Percent $\frac{\Delta k}{k} = \left(\frac{k_i - k_{i-1}}{k_1}\right)100.$

the order of P_l approximation from P_1 to P_o increases the multiplication factor by 0.77 percent $\Delta k/k$. Reducing the number of energy groups from 13 to 4 and the order of the S_n quadrature from 4 to 2 results in reductions in k_{eff} of 0.07 and 0.23 percent $\Delta k/k$, respectively.

Table V lists similar information for the poison-drums-out configuration. The overall effect of reducing the calculation level from S_4P_1-14 groups to S_2P_o-8 groups is a 0.07 percent $\Delta k/k$ reduction in the multiplication factor. Again considering the individual effects, the reduction in the level of the P_l approximation at 0.43 percent $\Delta k/k$ is still the most important. However, it is more than offset by the combined negative effects of the relatively constant S_n level change (-0.22 percent $\Delta k/k$) and the greatly increased energy group effect (-0.28 percent $\Delta k/k$). Calculations with four energy groups proved to be entirely inadequate for this configuration. The values of the multiplication factor for a BeO reflected critical assembly have shown a strong group dependence when calculated with the same procedure as that employed herein (ref. 3).

TABLE V. - MULTIPLICATION FACTOR FOR SMALL CORE WITH POISON DRUMS OUT AT VARIOUS LEVELS OF ONE-DIMENSIONAL CALCULATION

Index, i	Level of calculation	Neutron multiplication factor, k_{eff}	Control swing,[a] percent $\Delta k/k$
1	S_4, P_1, 14 groups	1.11429	----
2	S_4, P_o, 14 groups	1.11904	0.43
3	S_4, P_o, 8 groups	1.11597	-.28
4	S_2, P_o, 8 groups	1.11351	-.22
		Total effect	-0.07

[a] $\text{Percent } \frac{\Delta k}{k} \doteq \left(\frac{k_i - k_{i-1}}{k_1}\right)100.$

Two-Dimensional Geometries

The TDSN program has two-dimensional capability in the x, y and r, z geometries. Two-dimensional calculations in the radial plane must be done with the x, y geometry. The drums-full-in or full-out configurations are symmetric about these axes and "one-quarter-core" symmetry conditions utilizing plane optical reflection boundary conditions on the angular fluxes can be used. Intermediate drum positions meet "half-core," 180°

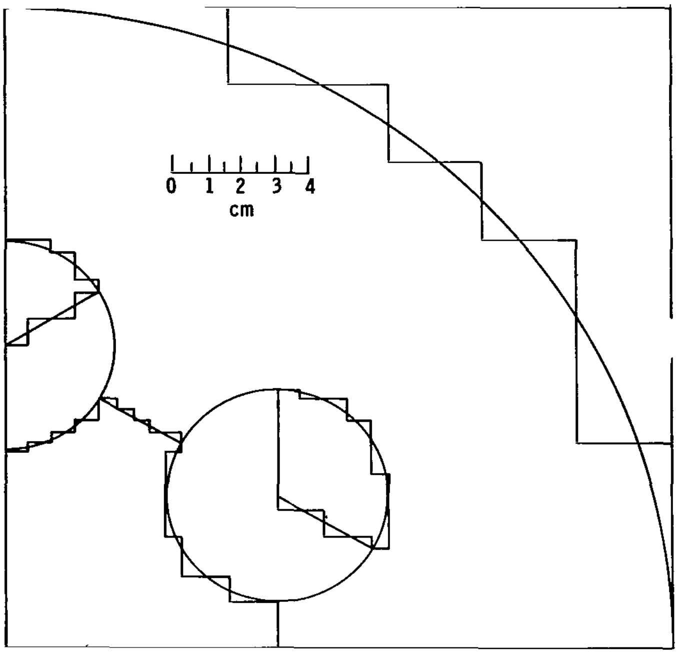

Figure 5. - Two-dimensional, one-quarter-core representation of fuel-drums-out configuration of small core.

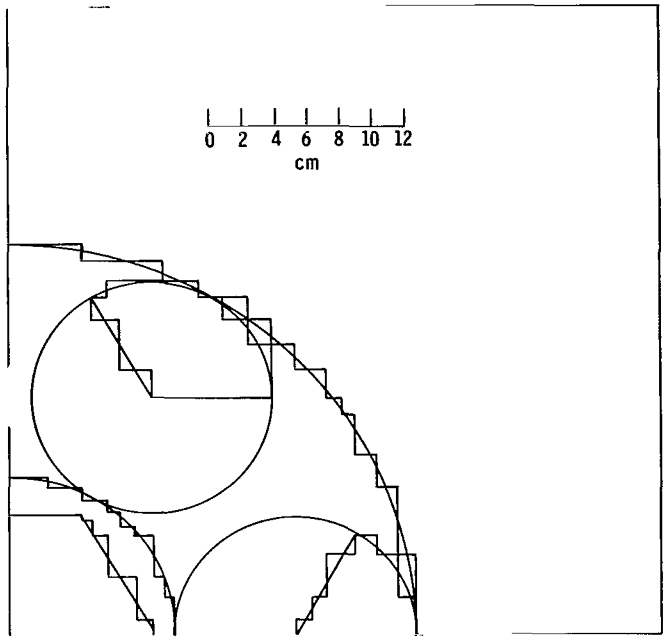

Figure 6. - Two-dimensional, one-quarter-core representation of poison-drums-out configuration of small core.

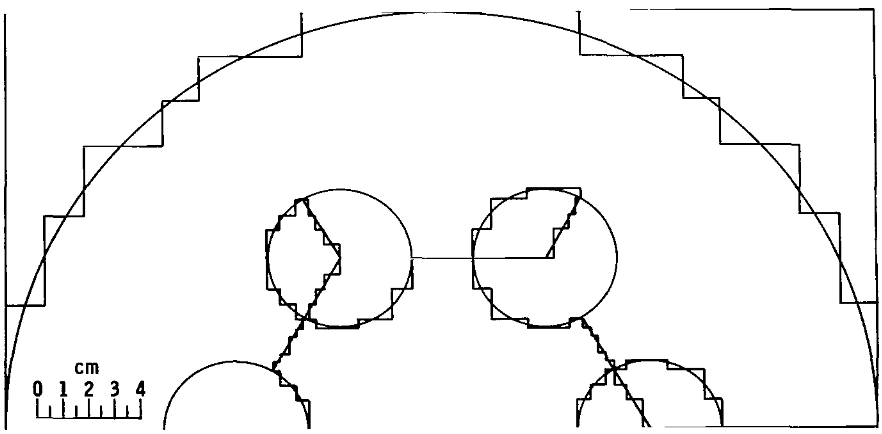

Figure 7. - Two-dimensional, half-core representation of fuel-drums-rotated-120°-out configuration of small core.

rotational symmetry conditions. Successive drums may be rotated in either the same or opposite directions. Power distortion is less severe with all drums rotated in the same direction. Note that the rotational scheme is immaterial for the drums-full-in or full-out positions.

Figures 5 to 8 are representative of the half-core and quarter-core geometries used in the calculations. The x, y representations are superimposed over the actual region boundaries. Identification of the several regions can be made through comparison with figures 1 and 2. The material descriptions are identical to those of the actual geometries.

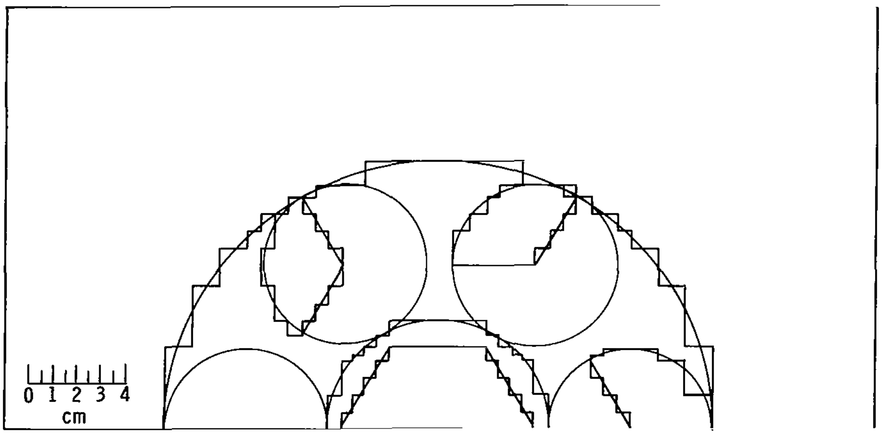

Figure 8. - Two-dimensional, half-core representation of poison-drums-rotated-120°-out configuration of small core.

TABLE VI. - SMALL-CORE MULTIPLICATION FACTORS AND CONTROL SWINGS FROM TWO-DIMENSIONAL CALCULATIONS

Drum rotation from shutdown, deg	Fuel drum[a] configuration	Poison drum[b] configuration
	Neutron multiplication factor, k_{eff}	
180	1.1026	1.1125
120	1.0827	1.0971
60	1.0436	1.0202
0	1.0272	.9908
Total control swing, percent $\Delta k/k$	7.34	12.28

[a]S_2, P_0, 4 groups.
[b]S_2, P_0, 8 groups.

Evaluation of One-Dimensional Model

Multiplication factors as calculated in two dimensions for each drum concept at four angular positions are given in table VI. The calculated values of the control swings represent the percentage variations of the effective multiplication factors through drum rotation from the minimum obtainable values. The corresponding units are expressed as percentage of $\Delta k/k$. The values of the fuel and poison drum control swings from the two-dimensional calculations listed in table VI are 7.34 and 12.28 percent $\Delta k/k$, respectively.

Low-order, one-dimensional calculations with the drum configurations in the shutdown positions were made to supplement the k_{eff} values given in tables IV and V. The multiplication factors for the fuel and poison drum configurations are 1.0383 and 0.9996. The control swings obtained with the one-dimensional model are 7.51 and 11.4 percent $\Delta k/k$ for the fuel and poison drum systems. These values agree to within 7 percent with the values derived from two-dimensional calculations. The one-dimensional model appears to be adequate for analyzing drum control worths of configurations similar to those presented herein.

The one-dimensional model was used exclusively for calculating the drum control worths for the intermediate and large configurations. All configurations were analyzed with S_4P_o discrete transport calculations with 13 energy groups in the fast and the epithermal regions (> 0.414 eV). The BeO reflected configuration was analyzed with an additional thermal group. In several calculations the use of spectrum-averaged cross sections varied from the practice of using only one set of cross sections to represent a material in all regions of the configuration. The use of additional spectrum-averaged cross-section sets is shown in the presentation of the various configurations. This represents the only variation from the analytical procedure described in this section of the report.

SUPPLEMENTARY INFORMATION CALCULATED WITH 16.5-CENTIMETER-EQUIVALENT-DIAMETER CORE

Effects of Peripheral Radial Shielding Materials on Control Swings

The ^6LiH region shown in figure 1 was increased from 2.5 centimeters to a thicker shield for this study. Additional low-order, one-dimensional calculations were performed with the shielding material removed and no-return-current boundary conditions at the outer edge of the reflectors. The anticipated reduction in the multiplication factors was about the same (~0.3 percent $\Delta k/k$) for the drums-in and the drums-out calculations. Thus, the control swings underwent negligible effects; the largest change in the control swings was a reduction of 0.08 percent $\Delta k/k$ for the poison drum configuration.

Control Response Curves

As in systems using rod control, the responses of the drum control system to changes in drum position correspond to S-shaped curves. The fractional control swings at four drum positions are compared with a $\sin^2(\theta/2)$ curve in figure 9. The agreement between the calculated points and the curve is within 15 percent at the worst point.

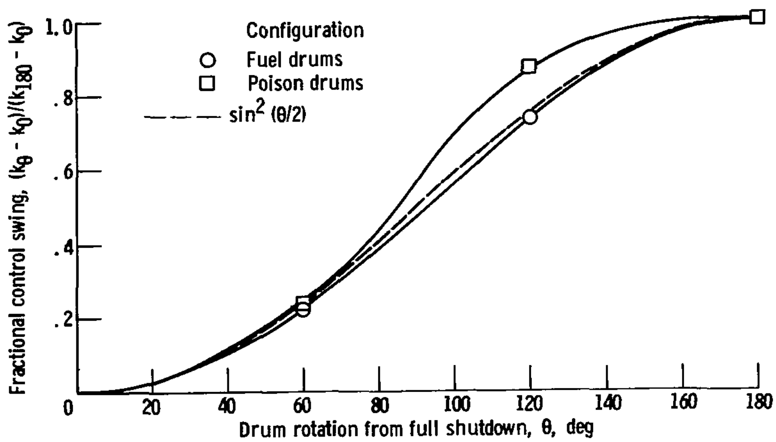

Figure 9. - Angular dependence of control reactivities compared with $\sin^2(\theta/2)$ curve. Total control reactivities normalized to 1.0.

Maximum to Average Radial Power Ratios

Because of the unsymmetric flux distributions around the peripheries of the cores, the power ratios are obtainable only from two-dimensional calculations. These ratios are listed in table VII. Of interest is the fractional change in the ratios with drum rotation, shown in figure 10. The curve representing the poison drum configuration rises more abruptly than that of the fuel drums. Each type of drum control has a flat, relatively insensitive region associated with the active portion of the drums being away from the core. The largest power ratios under operational conditions occur at the beginning-of-life, hot critical drum position where the only excess reactivity being held down is that allowed for fuel depletion. The power ratios at this drum position would be much closer to the minimum values at full reactivity insertion than to the maximum calculated

TABLE VII. - RATIOS OF MAXIMUM LOCAL RADIAL POWER DENSITY RELATIVE TO CORE AVERAGE FROM TWO-DIMENSIONAL CALCULATIONS OF EACH DRUM CONCEPT ON SMALL CORE

Drum rotation from shutdown position, deg	Fuel drum configuration	Poison drum configuration
	Power ratio, P_{max}/P_{av}	
0	1.43	1.37
60	1.39	1.30
120	1.31	1.20
180	1.25	1.19

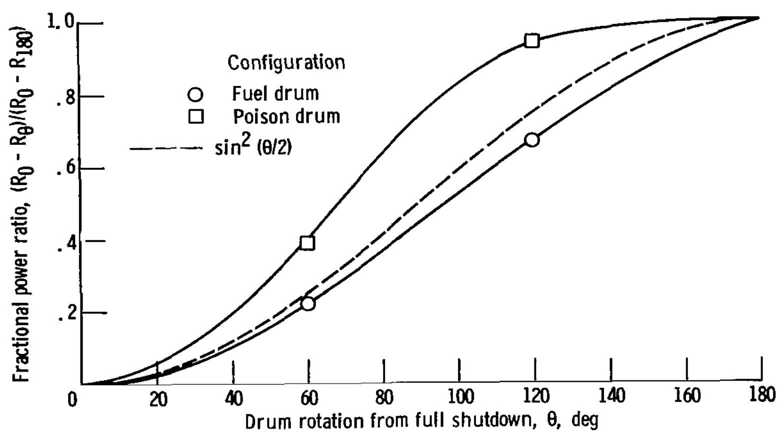

Figure 10. - Angular dependence of power ratios. Total change in power ratios normalized to 1.0.

values corresponding to the full shutdown position. For a given fuel depletion reactivity requirement, the curves in figures 9 and 10 could be used to determine the beginning-of-life, hot critical power ratio.

Relative Worths of Equal-Size Fuel and Poison Control Drums

The diameter of the poison drums shown in figure 2 was reduced to the fuel drum diameter of 6.35 centimeters for this comparison. Also the BeO reflector thickness was reduced to make the combined pressure vessel and reflector thickness correspond to the W reflector thickness of 10.16 centimeters. Low-order, one-dimensional calculations of the drums-in and drums-out multiplication factors yielded a control swing of 4.62 percent $\Delta k/k$. The control worth of equal-size fuel drums is 7.51 percent $\Delta k/k$.

INTERMEDIATE-SIZE CONFIGURATIONS WITH CORE DIAMETERS OF APPROXIMATELY 40 CENTIMETERS

Fuel Drums With Tungsten Reflector

A radial cross-section view of this configuration is shown in figure 11. The descriptions of the materials present in the intermediate and large configurations are given in table VIII. The 40.37-centimeter-diameter core is surrounded radially by a 10.16-centimeter-thick W reflector. The diameter of the control drums is 12.7 centimeters. The effective core height used to calculate the axial buckling is 48.87 centimeters.

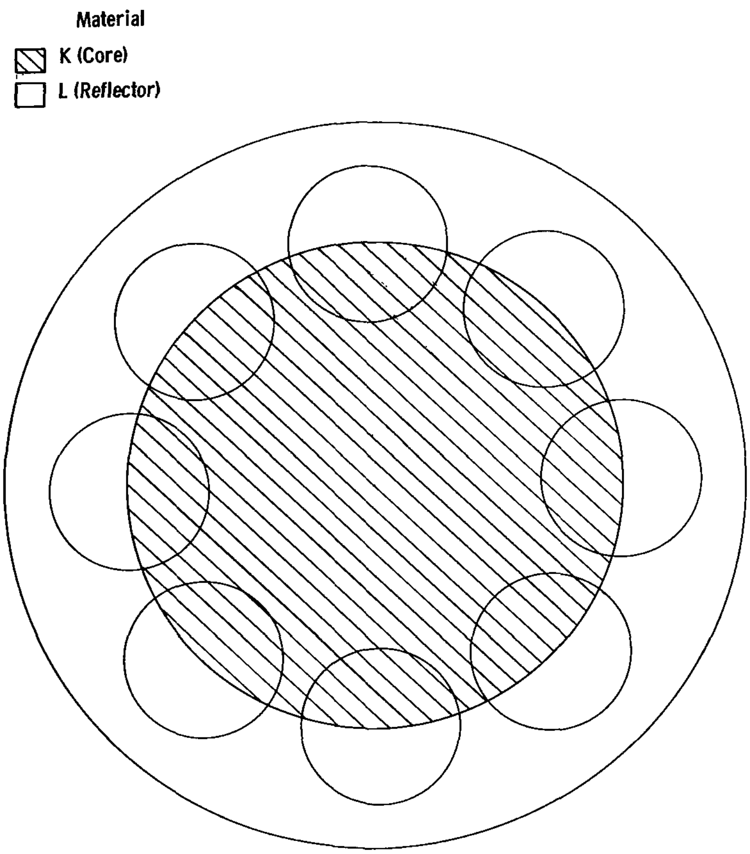

Figure 11. - Radial cross-section view of fuel drums, tungsten reflected configuration; core diameter, 40.37 centimeters.

TABLE VIII. - INTERMEDIATE- AND LARGE-CORE

MATERIAL DESCRIPTIONS

Material designations and constituents	Nuclide	Atom density, atoms/b-cm
Material K (core), vol. %:	^{233}U	0.00584
$^{233}UO_2$ fuel, 24	O	.01168
W cladding and structure, 27.1	W	.01713
^{7}Li coolant, 22.2	^{7}Li	.00793
Material L (tungsten reflector)		
Same as material B in table I		
Material M (core), vol. %:	^{233}U	0.00645
$^{233}UO_2$ fuel, 26.5	O	.01290
T-222 cladding and structure, 26		
87.5 wt. % Ta	Ta	.01267
10.0 wt. % W	W	.00142
2.5 wt. % Hf	Hf	.00037
^{7}Li coolant, 22.2	^{7}Li	.00793
Material N (molybdenum reflector), vol. %:		
Mo, 90	Mo	0.05769
^{7}Li, 10	^{7}Li	.00357
Material O (tantalum absorber), vol. %:		
Ta, 90	Ta	0.04977
^{7}Li coolant, 10	^{7}Li	.00357
Material P ($^{10}B_4C$ poison), vol. %:	^{10}B	0.08872
$^{10}B_4C$, 85	C	.02218
^{7}Li coolant, 15	^{7}Li	.00536
Material Q (T-222 pressure vessel)		
Same as material E, table I		
Material R (reflector), vol. %:	Be	0.02424
BeO, 34	O	.02424
Mo, 29	Mo	.01859
^{7}Li, 15	^{7}Li	.00536
Material S (core) vol. %:	^{233}U	0.00365
$^{233}UO_2$ fuel, 15	O	.00730
T-222 cladding and structure, 26	Ta	.01267
	W	.00142
	Hf	.00037
^{7}Li coolant, 22.2	^{7}Li	.00793

Fuel Drums With Molybdenum Reflector

This configuration is shown in figure 12. Here the core diameter is 39.8 centimeters and the effective height is 48.3 centimeters. A 10.16-centimeter-thick radial reflector surrounds the core. The reflector portion of the 12.7-centimeter-diameter drums contains tantalum (Ta) absorber regions which enhance the neutronic separation of the fuel portion of the drums from the core. The 2.54-centimeter-thick Ta segments arc about 120° of the drum circumferences. In calculating the multiplication factor for the drums-out configuration, the fuel and reflector portions of the drums were represented by cross sections that were averaged over the surrounding reflector and core spectra, respectively.

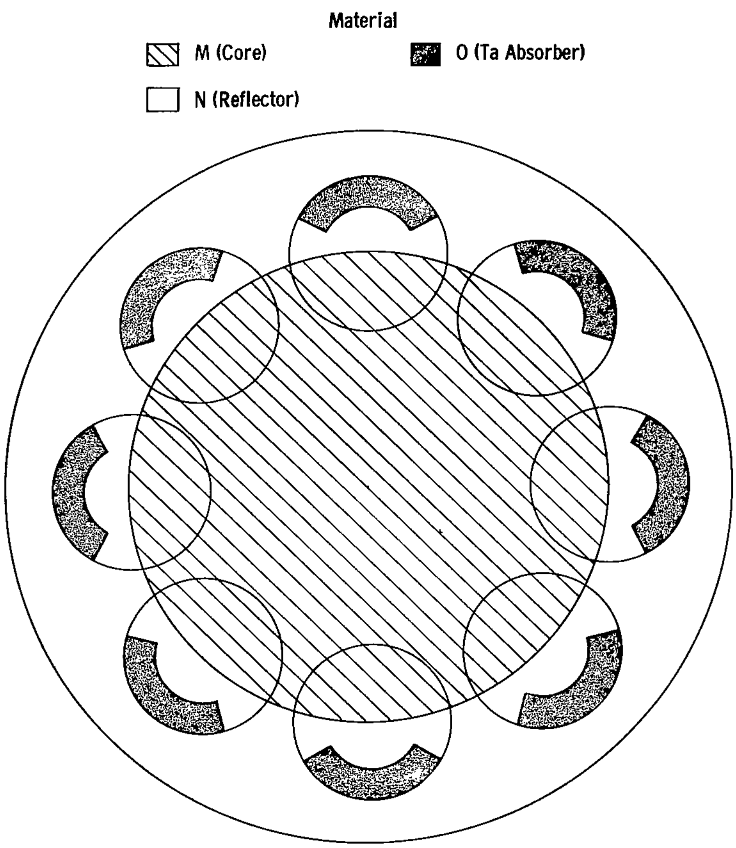

Figure 12. - Radial cross-section view of fuel drums. Molybdenum reflected configuration; core diameter, 39.8 centimeters.

Poison Drums With Beryllium Oxide Reflector

The core of this configuration (shown in fig. 13) is exactly the same as the core in the molybdenum reflected configuration. A 1-centimeter-thick pressure vessel surrounds the core. External to the pressure vessel is a 20.32-centimeter-thick BeO reflector containing the control drums. The 6.35-centimeter-thick $^{10}B_4C$ portions of the control drums extend over 154° arcs. The drum diameter is 20.32 centimeters. In the analysis the pressure vessel was divided into two regions of equal thickness. The inner region was represented by core-spectrum-averaged cross sections, and the outer region was represented by reflector-spectrum-averaged cross sections. The thermal group cross sections for all materials were averaged over the reflector spectrum. This procedure was necessitated by the lack of a moderator to determine a core thermal spectrum.

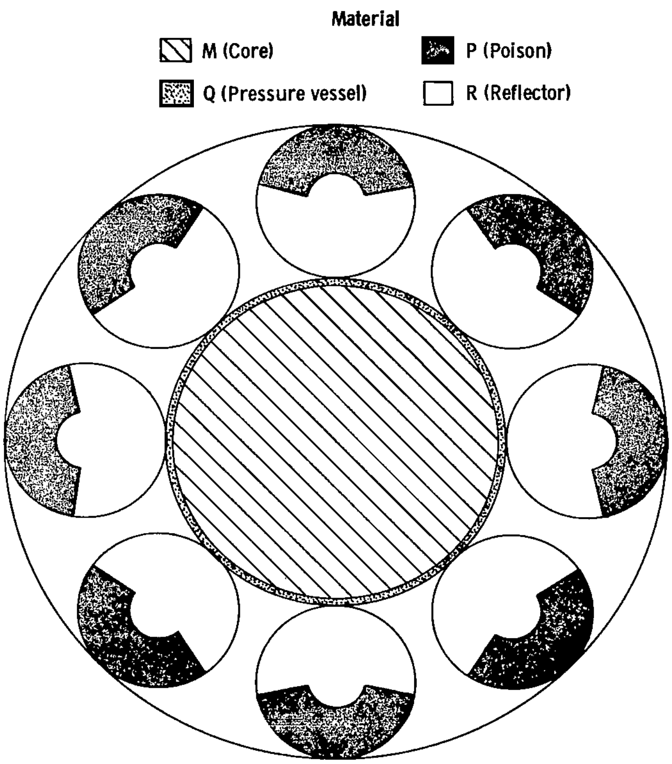

Figure 13. - Radial cross-section view of poison drums. Beryllium oxide reflected configuration; core diameter, 39.8 centimeters.

Calculated Control Drum Worths on Intermediate-Size Cores

The calculated drums-in and drums-out multiplication factors and the corresponding control swings are presented in table IX. All three intermediate-size configurations are capable of providing in excess of 9 percent $\Delta k/k$ control swing.

TABLE IX. - CALCULATED MULTIPLICATION FACTORS AND CONTROL SWINGS FOR INTERMEDIATE-SIZE CONFIGURATIONS

Configuration	Neutron multiplication factor, k_{eff}		Control swing, percent $\Delta k/k$
	Maximum	Minimum	
Fuel drums with W reflector	1.06016	0.96769	9.556
Fuel drums with Mo reflector	1.06101	.96121	10.383
Poison drums with BeO reflector	1.09673	.98648	11.176

LARGE-SIZE CONFIGURATIONS WITH CORE DIAMETERS OF 80 CENTIMETERS

Fuel Drums With Molybdenum Reflector

A radial cross-section view of this configuration is given in figure 14. The 29-centimeter-diameter drums have a separation of only 1.6 centimeters. This gap is probably less than that which the fabricator would consider practical. The large drum diameter was chosen so that the control swing would approach the upper theoretical limit without being entirely unrealistic about the need for a separation between the drums. The molybdenum reflector is 14.5 centimeters thick. The core height used to calculate the axial buckling is 75.0 centimeters.

Poison Drums With Beryllium Oxide Reflector

This configuration is shown in figure 15. A 2-centimeter-thick T-222 pressure vessel surrounds the core. The analysis included splitting the pressure vessel into two

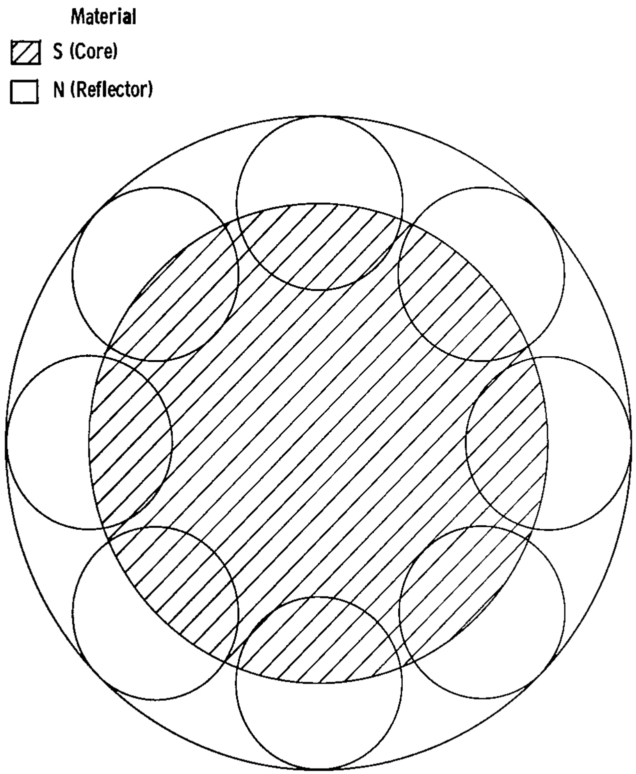

Figure 14. - Radial cross-section view of fuel drums. Molybdenum reflected configuration; core diameter, 80 centimeters.

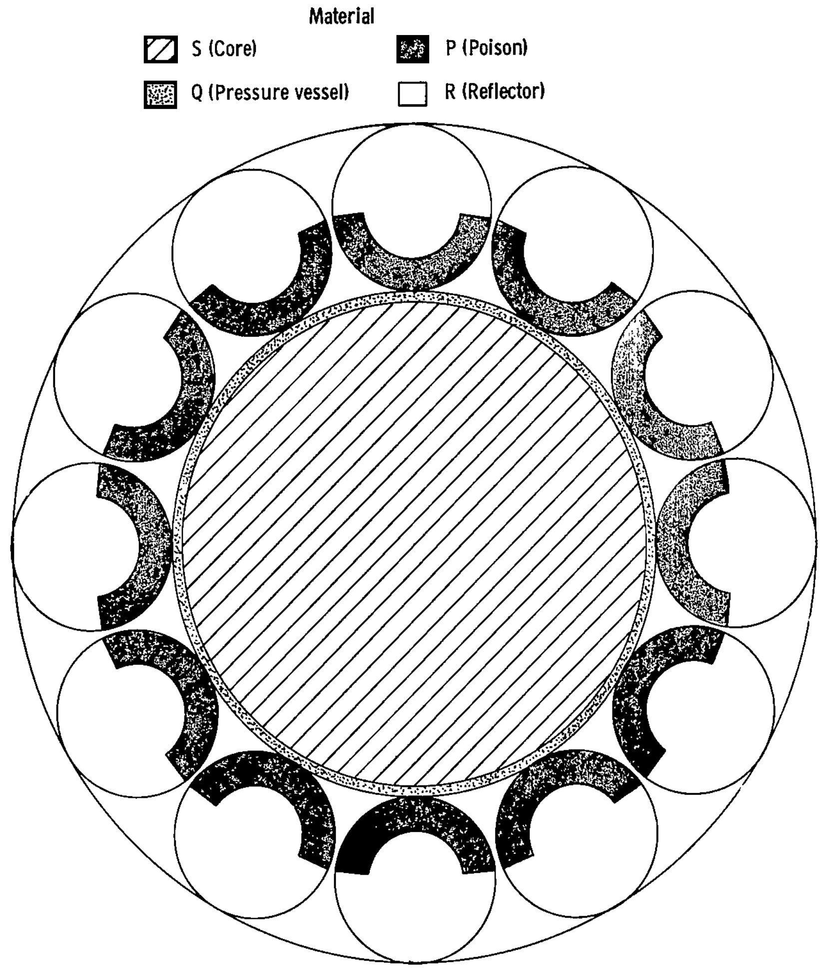

Figure 15. - Radial cross-section view of poison drums. Beryllium oxide reflected configuration; core diameter, 80 centimeters.

regions of equal thickness with core- and reflector-spectra-averaged cross sections used in the inner and outer regions. As in the large-core fuel drum configuration, the control drums were designed with a near-maximum diameter for this geometry of 28 centimeters. The separation between the drums is 1 centimeter. The 6-centimeter-thick $^{10}B_4C$ vanes subtend 168° of the drum peripheries. The control swing was calculated for the same configuration without the pressure vessel so that its effect upon the control swing could be demonstrated.

Calculated Control Drum Worths on Large Core

The calculated drums-in and drums-out multiplication factors and the associated control swings for the large core are given in table X. The fuel drum control swing of 11.4 percent $\Delta k/k$ demonstrates that this type of control is adequate for large-diameter cores. The poison drum control swing is significantly reduced by the presence of the 2-centimeter, T-222 pressure vessel. The control swing drops from 8.45 to 3.76 percent $\Delta k/k$. The thermal-neutron power spike which often occurs near a core - BeO-reflector interface does not occur here even when the pressure vessel is removed. The lack of a power spike is attributed to the high Mo - low BeO content of the reflector and the relatively low fuel density in the core. Thus, the pressure vessel is not needed to remove a power spike. However, it is doubtful that a significantly thinner pressure vessel would have sufficient strength properties. Optimization of this system would probably involve placing the pressure vessel outside the reflector and equalizing the temperature capabilities of the core and the reflector, supposedly without decreasing the no-pressure-

TABLE X. - CALCULATED MULTIPLICATION FACTORS AND CONTROL SWINGS FOR LARGE-SIZE CONFIGURATIONS

Configuration	Neutron multiplication factor, k_{eff}		Control swings, percent $\Delta k/k$
	Maximum	Minimum	
Fuel drums with Mo reflector	1.0985	0.9860	11.4
Poison drums with BeO reflector	1.0856	1.0463	3.76
Poison drums without pressure vessel	1.1184	1.0313	8.45

vessel control swing. In any event, the 3.76 percent $\Delta k/k$ control swing of the configuration presented herein would not be sufficient for applications requiring large control reactivities for fuel burnup or reactor shutdown.

SUMMARY OF RESULTS

Two control methods for refractory-metal, fast-spectrum reactors were studied. A one-dimensional model was developed to calculate the control worths of fuel and poison drum systems on small, intermediate, and large space power reactors (core diameter, approx. 17, 40, and 80 cm). The one-dimensional model was evaluated by comparison of one- and two-dimensional calculations of drum control worths on the small core. The values of the fuel and poison drum control worths of 7.5 and 11.4 percent $\Delta k/k$ agree to within 7 percent with the values from two-dimensional calculations of 7.3 and 12.3 percent $\Delta k/k$.

Either type of drum control is capable of providing in excess of 7 percent $\Delta k/k$ for the small- and intermediate-size reactors. The large-core configurations were calculated with near-maximum-size drum geometries to show the advantage of fuel drums over poison drums for large-diameter reactors. The fuel drum configuration, with 47 percent of the core volume in the drums, has a calculated control swing of 11.4 percent $\Delta k/k$. The poison drum control swing of 3.8 percent $\Delta k/k$ would probably be of marginal value for systems requiring considerable reactivity for burnup or shutdown or both.

Fuel drums are also more effective than equal-size poison drums. The calculated control swings for 6.35-centimeter-diameter fuel and poison drum systems were 7.5 and 4.6 percent $\Delta k/k$, respectively.

Two-dimensional calculations were performed for each drum system on the small core to determine the effect of drum angular position on the multiplication factors. The multiplication factors calculated at drum rotations of 0°, 60°, 120°, and 180° from shutdown indicate the shapes of the control response curve. Comparison of the fractional control swing data with an S-shaped $\sin^2(\theta/2)$ curve shows an agreement to within 15 percent at the worst point.

The maximum to average radial power ratios were obtained for the small-core configurations from two-dimensional calculations at four drum positions. The largest values occur for the configuration with drum systems at the shutdown position. These ratios are 1.43 and 1.37 for the fuel and poison drums, respectively. Under operational conditions the largest power ratios would occur at beginning of life, hot critical. These ratios would be much closer to the calculated values at full reactivity insertion of 1.25 and 1.19.

The effect of radial shielding material on the control swings of the small-core configurations was studied with one-dimensional calculations. The shielding material reduced the radial leakage, thereby increasing the multiplication factors. However, the increase in the multiplication factors was almost the same for the drums-in and drums-out configurations. Thus, the effect on the control swings was negligible.

Lewis Research Center,
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Cleveland, Ohio, May 7, 1968,
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